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Germanium varistors

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GERMANIUM VARISTORS

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PREFACE

The writer wishes to thank the Bell Telephone Laboratories for the priviledge of working in their laboratories from January 3, 1949 to March 15, 1949. He wishes to express his appreciation to the many members of the laboratories who freely gave information. Also to Professor Carl E. Menneken of the faculty of the U. S. Naval Postgraduate School for his constructive criticism and advice in the preparation of this paper.

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INTRODUCTION

A survey of the high inverse voltage germanium rectifier or germanium varistor. The history of the development of this unit during the war and earlier is covered. The theory of conduction and rectification as presently held is described from a qualitative viewpoint. The outstanding properties, both mechanical and electrical, and their dependence on the manufacturing techniques are investigated. These are later linked to the uses to which these units are or may be placed showing how they are effected.

CHAPTER I

HISTORY

At the beginning of the war there was widespread use of the 'contact' type of semiconductor such as copper oxide and selenium. In these, discs of copper oxide, or selenium, properly prepared, were arranged in stacks whose diameter and number varied with the amount of power the particular unit was designed to handle. These devices could pass a few microamperes of current or 100,000 amperes; a few microvolts or 1,500,000 volts. The primary use of these devices was, and still is, as a rectifier for power purposes. Small copper oxide units were widely used in the telephone industry for various purposes. (10, 27).

There were relatively few 'point-contact' type semiconductors, such as those using silicon and galena, in use. These consisted, in general, of a crystal, a small piece of silicon or galena, which was soldered to a metallic base. A fine tungsten wire, or cat's whisker, made contact with the other surface. It was necessary to move the metallic whisker about from time to time to find a more 'sensitive' spot, and thus obtain better conduction. This type of crystal was used in the crystal radio sets as detectors and, better ones of silicon, were often used in the laboratory in instruments. They were of limited current and voltage handling ability.

With the advent of radar requiring high gain receivers the amount of noise introduced internally had to be kept as low as possible. As the mixer stage was the greatest single contributor of noise, steps were taken to improve the mixers in use. A result of this was to reinvestigate the use of crystals which had been in wide use in the days prior to the vacuum tube. The work which followed on silicon, germanium, and boron resulted in the development of the 1N21 and 1N23 series, the 1N25, the 1N26 and the 1N28 silicon crystals which were widely used in wartime radar sets. Boron failed to show sufficiently good properties to be of use. Germanium exhibited very good qualities, but they were not sufficiently developed to be of use during the war.

Germanium, one of the rarer metals, is usually found in combination with one or more metals. Its existence was predicted by Mendeleeff in 1871; it was discovered by Winkler in 1886. (13). Bidwell (5) in 1922 showed that it had a large negative resistance coefficient with increasing temperature. There was considerable work done in the late 1920s in establishing its physical properties and investigating its possible uses. No practical use seems to have been made of germanium until it was discovered that, properly prepared, it was an excellent point-contact rectifier.

This discovery came about during the intensive research which was conducted by various groups during the war. There were two major types of point-contact germanium semiconductors developed. One was the high inverse voltage type which was developed as a result of the investigations of the group at

Purdue University. (25) The second was the welded contact germanium semiconductor (19) which was developed at General Electric.

The welded contact type exhibited the unusual property of conversion gain when used as a mixer in the microwave region. Unfortunately, the noise figure of this unit was worse than that of the silicon units to such an extent that no advantage was obtained by using these units in lieu of the silicon. This type unit is used in the microwave region and will not be covered in this paper.

The high inverse voltage type was found to be unsuitable for use at frequencies greater than 100 Mcs. At lesser frequencies, from 30 Mcs. down, this unit seemed capable of being of great value in second detectors, d-c restorers, diode modulators, and switching circuits. After the war the study of germanium semiconductors continued at many places.

The high inverse voltage germanium rectifier is manufactured by Sylvania as the 1N34, by Western Electric and by General Electric as the 1N43, 1N44, 1N45, and 1N46.

In the literature the high inverse voltage germanium rectifier appears under many names, such as, crystal diode, crystal valve, point-contact rectifier, germanium rectifier, varistors, germanium diodes, and the like. Varistor a Bell Telephone Laboratories coined word from the two words 'variable' and 'resistor' is probably the most accurate single word in describing the attributes of these units. This term will be used in this paper.

CHAPTER II

THEORY

In the following discussion of theory, a qualitative point of view is taken. The theory of rectification is still in a state of flux. Predictions have not been completely borne out by experiments. There will undoubtedly be significant changes in theory in the next few years.

1. Band Theory

Modern theory (23, 24) holds that the atom consists of a nucleus with associated electrons, the number of which vary with the element. As a consequence of quantum mechanics, these electrons are considered to possess certain discreet energies. These energies may be thought of as levels. These levels are limited as to the number of permissible sub-levels or energy states that may exist within them. According to Pauli's exclusion principle only one electron may occupy a sub-level. As atomic number is increased the lowest levels are filled, then the upper until the ultimate is reached. Those levels which are completely filled are stable, that is to say, their electrons do not readily wander away from the nucleus. Those levels which have vacant energy states are relatively unstable. The few electrons within these unfilled levels may, under the influence of heat or electrical energy, wander about the various sub-levels. These electrons are designated the valence electrons.

When individual atoms combine to form a crystal structure, the nuclei arrange themselves in a lattice type of structure with each nucleus surrounded by its electrons. Those electrons which are in the filled levels are closely bound to the nuclei and remain fixed. The valence electrons being loosely bound, are able to move through the lattice at random.

The exclusion principle, still valid, limits the energy that may be possessed by an electron. Further, the energy levels are still in discreet steps. The lowest energy which is possessed by any of the valence electrons is -W where W is the amount of energy in electron volts required to remove the electron from inside of the metal to a point just outside of the metal when the temperature of the metal is zero absolute.

These discreet energy states that the valence electrons may possess may be thought of as grouped in bands. The number of energy states in each band corresponds to the number of atoms in the total lattice structure. There are two possible arrangements of these bands; one, that the bands be continuous; two, that bands be separated by 'forbidden' regions. Regions possessing energy levels that the electrons may not possess are called 'forbidden' regions. An allowed band which has all of its available levels occupied is called a filled band.

The second of these two arrangements of the bands may be divided into three subdivisions; one, the allowed band will have some of its levels vacant; two, the allowed bands will be completely filled and the forbidden region will be of great width; three, the allowed band will be completely filled but the forbidden region will be narrow.

The first arrangement and the first subdivision of the second are typical of conductors, usually metals. In these cases the presence of unfilled levels immediately adjacent to the filled levels shows that the electrons in this type of substance require but a little energy from outside sources to be able to conduct.

The last two subdivisions of the second arrangement are true of insulators and semiconductors respectively. In the case of the insulators since the allowed band is filled, the electrons can not move without the application of outside forces. This is something similar to the situation that would exist if the bottom of a box were completely covered with marbles. None of them could roll about until an outside force removed some of them. In the case of the insulator, the outside force could be either heat or an electric field. The energy required would, for good insulators, be of the order of several electron volts. This would require the application of electric fields or heat of magnitudes not normally met in practice.

In the case of the semiconductors, the width of the forbidden region is of the order of one electron volt. Thus, with these materials, small fields and small temperature increases are necessary to impart sufficient energy to the electrons in the upper levels of the allowed bands to permit them to bridge the gap and move freely about. This is true of both germanium and silicon. Conduction of this type is known as intrinsic conduction.

With the application of heat to a semiconductor, there are two types of conduction occurring simultaneously. The fact that sufficient energy has been given to some of the electrons to permit them to cross the forbidden region means that there are 'holes' in the lower band. The electrons which have crossed are able to move under the influence of an applied electric field and conduct. Due to the removal of electrons from the lower band there are now 'holes' or unfilled energy states. The flow of electrons in this case is such as to give the effect that positively charged bodies are conducting.

If the semiconductor has a small amount of impurity present, conduction upon applying a field will take place at room temperature due to the excess of electrons which are supplied by the impurity or by the lack of electrons due to the impurity. This type of conduction is known as extrinsic conduction.

Germanium, as currently used, is an extrinsic semiconductor. It has been shown that pure germanium (23) must be solely an intrinsic semiconductor since lattice defects can not exist in an ideally perfect crystal. However, it has not been possible to produce pure germanium. The best that has been produced so far has had an impurity of the order of one part per ten million. (22). This amount, small as it is, is still sufficient to cause extrinsic conduction.

At low temperatures, conduction in germanium is extrinsic. With increasing temperatures, the conduction becomes intrinsic. The presence of impurities will enhance the conduction effect. It has been possible to calculate the conductivity of a sample of germanium over a wide range of temperatures and to have excellent agreement between calculated and observed values (14).

There are two types of extrinsic conduction, the N type and the P type, that is, by electrons or by holes. The first is due to donator levels; the second to acceptor levels.

When impurities are introduced in a lattice structure localized defect areas are setup. In the case of germanium, if the introduced impurity is from the fifth column of the periodic table, the impurity atom will have an excess electron. This will result in the electron possessing energy which is normally forbidden to germanium electrons. This electron will lie in the forbidden region very close to the unfilled bands. Upon the application of an electric field, this electron will be able to take energy from the field, gain the upper allowed levels, and move freely about causing conduction.

If the impurity is from the third column of the periodic table, it will have three instead of four valence electrons as does germanium. This will result in levels which are unfilled which will lie in the forbidden zone near the filled lower band. Under the application of an electric field, the higher energy electrons in the filled band will absorb more energy and will jump to the empty, or acceptor, levels. Due to the localized effect of the impurity, they are restrained from free motion, but the removal of electrons from the filled band has created unfilled levels, electrons in the lower band may now move under the influence of the applied field. As pointed out, this gives rise to an effect which seems to indicate that conduction is taking place by means of positively charged particles.

2. Theory of Rectification

The generally held theory of rectification in semiconductors is based on the difference in work functions of the metallic contact and the semiconductor. According to this theory a double layer exists between the metal and the semiconductor. This layer consists of a charge on the metal and a space charge extending into the semiconductor for a depth of 10^{-6} to 10^{-4} cm. This barrier or potential hill formed by this double layer is such that, in the case of an excess semiconductor, the surface of the semiconductor has a positive charge. If a negative voltage is applied to the base of the semiconductor, a decrease in the height of the barrier, as seen by the semiconductor, results which permits a flow of current. If the opposite polarity is applied to the semiconductor, the height of the barrier is increased and the flow of current sharply reduced.

With this theory based on the differences in work functions, it should follow that use of metallic contacts whose work functions were markedly different from the work function of tungsten would cause a higher or lower barrier to exist and thus a higher or lower back resistance. Also, the same contact would not be expected to rectify equally well for both N and P type semiconductors. These conditions have not been completely observed in experimentation. In some cases good agreement between the theory and experiment have been obtained but, as often, no agreement has been obtained. (6).

A theory which explains some of the effects which were noted by experiment but not previously explained has been developed by Bardeen. (1).

This theory postulates that in addition to the double layer which is caused by the difference in work functions there are double layers which are a result of surface states due to foreign atoms located on the surface or to lattice defects; that there are double layers on both the metal and the semiconductor due to the chemical body properties of the two metals. These additional layers introduce more energy levels.

If the surface states have a high density they will contribute sufficient energy levels to overshadow the work functions and to determine the rectification characteristics. Conversely, if the surface states have a low density, the work functions will determine the rectification.

To explain abnormal current flow noted by Bray, (9), Brattain (8), has postulated that, in addition to the requirements of Bardeen's theory, there may be a film or thin layer of P type immediately adjacent to the surface which causes this increased current flow.

The theory of rectification which began as a relatively simple theory has become increasing complex as more divergences have been noted and special extensions or modifications have been made to cover them. There will undoubtedly be further additions to the theory but at present the theory is sufficiently well advanced to permit good use to be made of it, as witness the development of the transistor.

CHAPTER III

PROPERTIES

1. Electrical Properties

One of the properties of the high inverse voltage germanium semiconductor that makes it of great value is its wide range of resistance. In most varistors the inverse resistance is of the order of several hundred thousand ohms while the forward resistance is of the order of less than a hundred ohms. These resistance values vary from unit to unit over a rather wide range.

The change from a high back resistance to a low forward resistance occurs over the range of positive voltage from zero to approximately one volt. An exponential function may be fitted fairly well to this curve. (26). In most applications it is considered that the resistance goes abruptly from a high to a low value.

The back resistance is not a constant but varies with magnitude of applied voltage. It rises to a maximum value around -5 volts and then decreases slowly with increasing negative voltage until the voltage breakdown point is reached. At this point the current increases rapidly giving a large region of negative dynamic resistance. Voltage breakdown is usually 200 volts or less. Should the breakdown voltage be exceeded for a short time, the varistor will still be usable but will have a lower value of inverse voltage breakdown.

The usual picture of an equivalent circuit is a variable resistance shunted by a capacitance, both in series with the spreading resistance. The variable resistance is the non-linear resistance of the barrier. The capacitance is the capacitance of the barrier, also non-linear. The spreading resistance is the resistance determined by the conductivity of the sample and the area of the contact surface of the cat's whisker. This resistance is so much larger than the resistances due to the bulk of the semiconductor and to the tungsten wire that they may be neglected.

The characteristic of possessing a high back resistance and a low forward resistance is similar to the characteristics of diodes. There are several notable differences. One is that the back resistance of the varistor is lower and is variable. Another is that for zero applied voltage the current output of the varistor is zero. The voltage breakdown is much smaller for the normal varistor than for a diode. The current output of a varistor is much greater than for a diode such as the 6AL5 or 6H6. The characteristics of the varistor are temperature sensitive to a rather high degree. For constant applied voltage the current decreases with decreasing temperature. The temperature range for the Western Electric varistor is -40° C. to 70° C. The varistors have smaller input and output capacitances than do diodes. Electric transit time is less in the varistors.

Manufacturers specify values of current at certain voltages. For example, Western Electric specifies the minimum forward current at one volt d-c, the maximum reverse current at -50 volts, the maximum reverse current at -3 or -5 volts or both depending on the type varistor, the maximum forward currents, both peak and average, and the maximum inverse voltage, all at a temperature of 25°C. It should be noted that these values are limiting values. They do not specify fully any one varistor. To accurately specify any one varistor would require a large number of points on the voltage -current curve.

Varistors, being point-contact devices, are limited in current handling abilities. The normal diameter of the cat's whisker is 5 mils. Increasing this size causes deterioration of rectification properties and increases the capacitance of the barrier. The latter effect is of importance if the frequency at which the varistor is used is very high, since the increased capacitance will act as a better shunt. Although limited incurrent handling abilities in comparison with semiconductors such as copper oxide, the normal varistor can handle an average current of forty milliamperes.

The low capacitance, approximately 1 mmf, of the varistor gives it an essentially flat response to frequencies in excess of ten megacycles.

Provided the limits of voltage or current are not ex-

ceeded, these units are very stable. At present there are units which have been undergoing life tests for several thousand hours with no appreciable reduction in characteristics.

2. Mechanical Properties

The varistor is a very small device, only slightly larger than a half watt resistor. The exact dimensions are a length of half an inch and a diameter of a quarter of an inch.

Like a resistor varistors are equipped with long pigtail leads. These are usually of nickel alloy in order to reduce heat conduction from soldering. The temperature sensitivity of the varistor is such that poor soldering technique will change varistor characteristics.

Mechanically the units are very rugged. They may be dropped from moderate heights with no damage physically or electrically. The small size and ruggedness are very valuable assets. Combined with the electrical properties, they give the varistor the valuable property of requiring no maintenance.

CHAPTER IV

MANUFACTURING TECHNIQUES

The germanium varistors are prepared from germanium oxide which is a byproduce of zinc smelting. The germanium oxide is reduced in hydrogen to obrain pure germanium. A yield of ninety-five percent is obtained.

The pure germanium with, usually a few tenths of a percent, a small percentage of selected impurity is melted in an induction furnace. The induction furnace is normal except that it has been modified so that the induction coil may be raised at a controlled rate, usually about an eighth of an inch per minute. The ingot then solidifies from the bottom up.

It is a property of solids that when two or more with different freezing points are liquified and then solidified that the proportion of crystals of each solid varies with the rate of cooling. That is, if there are two solids whose freezing temperatures differ by several degrees, if the temperature is lowered to a little below the highest freezing point, the proportion of crystals of each element would be proportional to the temperature.

The preparation of germanium by this method causes the lower portion of the ingot to be composed of purer germanium than the upper. In fact, the majority of impurities is concentrated in the extreme upper portion of the ingot.

The ingot is next heat treated for twenty-four hours. This treatment consists of cooling the ingot at a slow rate from 800°C. It has been found that this heat treatment insures that all of the ingots will be of the N type and that all but the upper one-third of the ingot will be able to withstand more than 50 volts peak inverse. Prior to the introduction of this treatment it was found that the doped ingot frequently had a core of N type but the outer portion was P type.

After the ingot has been properly heat treated it is sawed into wafers which are .020 inches thick. These wafers are then diced into squares .040 inches on a side. One side of the square is copper plated for mounting, the other face is ground to a smooth surface with water and alumnia. These wafers are then mounted on hexagonal brass studs which are .125 inches in diameter and approximately .2 inches long.

The cat's whisker is manufactured of tungsten wire whose diameter is 5 mils. The whiskers are inserted in a stud similar to the wafer stud and soldered in. They are next formed into an S shape by use of a die. Fifty to a hundred of these studs with their whiskers are mounted in a rack for pointing. This rack is placed over an electrolyte bath into which the ends of the whiskers project. By controlling the level of the bath, the length of the whisker can be controlled. The tungsten wires are maintained at a constant voltage but due to the fact that the portion which is in the solution decreases in area, the current decreases.

This decrease in current is reproducible and is used to control the process.

As the tungsten passes into solution the portion which is completely submerged maintains its cylindrical shape. That portion which is wetted by the meniscus forms a taper. Finally the lower portion is completely dissolved leaving a sharp taper. The sharpness can be controlled by switching off the voltage when the current falls to any predetermined value.

The completed studs are mounted by pairs by force fitting into nickel collars of a bakelite holder which is a half inch long and a quarter of an inch in diameter. The amount of pressure exerted at this shape is just sufficient to cause the cat's whisker to make contact with the germanium crystal.

The cartridge is next placed in a micrometer which is connected to an oscilliscope so that the voltage-current curve of the varistor may be observed. Further pressure is applied to the studs which causes more of the cat's whisker to contact the surface of the germanium and give a better voltage-current relation. A slight amount of judicious tapping on the cartridge case will improve the inverse characteristic.

The varistor is next given a stabilizing power treatment which consists of applying 30 volt 60 cycle pulses for .8 seconds. This has the effect of increasing the back resistance and make the unit more stable.

Nickel alloy pigtail leads are soldered on to the collars. The unit is now ready for testing and classification.

The units are tested for maximum inverse voltage, minimum forward current, maximum reverse current at -50 volts. As a result of these tests the units are graded as 1N43, 1N44, 1N45 or 1N46. They are stamped with their RMA designation, manufacturer's name, and an arrowhead pointing in the direction of easy current flow.

CHAPTER V

USES

1. Modulators and Demodulators

As the germanium varistor grew out of the attempt to find a mixer for radar circuits, it is not surprising that one of the widest uses to which these units have been put is that of modulation or its converse, demodulation. In radio circuits the varistor has been used for a first detector or mixer, a second detector, an arc source, and combinations of two have been used as discriminators in F.M. detectors. In the telephone industry the germanium varistor has been used in place of copper oxide varistors for modulator and demodulator units.

In radio, one of the main advantages of the varistor as a detector has been the fact that its use gives a wider bandwidth detection. Consider the varistor as a diode, if the interelectrode capacitance is low, the i-f by-pass condenser may be small and yet of such size in relation to the interelectrode capacitance that the majority of the voltage is across the diode, then the value of the diode load will determine the bandwidth. The smaller the diode load resistance, the wider the bandwidth. At the same time, the higher the ratio of diode resistance to load resistance, the greater the efficiency of detection. Since the varistor has a very low capacitance and a very low forward resistance, it meets these requirements making an excellent wide band detector for high frequencies.

There are disadvantages. One is that the varistor is definitely limited in the amplitude of the applied voltage due to the inverse volt requirement. This, of course, effects the output voltage as well, Another is that the back resistance of a varistor is finite. This permits the unit to load the i-f stage. This loading varies with i-f voltage, frequency and from unit to unit.

There are other advantages in using varistors as detectors in radio circuits. The varistor requires no filament power, reducing power requirements and contributing no hum. The small size of the unit and the fact that it is equipped with pigtails permits it to be tucked away in the circuit in nearly any position. This obviates the need for sockets and extra wiring. Further, the varistor is more linear at lower voltages than a diode. The output current is higher, up to forty milliamperes, average.

In receivers having d-c feedback loops around individual stages to prevent overloading or having a logarithmic response detectors are required at plates of several i-f stages. The use of varistors for these detectors is of advantage since the interelectrode capacitance is so small that it has little effect on the gain -bandwidth figure thus simplifying design considerations.

In telephone circuits which use varistor units as modulators or demodulators the varistors are usually four in number and are arranged in a lattice form. There are two basic forms, the ring and the bridge type. These may be characterized by thinking of the ring type as a periodic phase reversing circuit and of the bridge type as a periodic shorting shunt arm. The ring type is more frequently used since its output consists, theoretically, of all odd carrier harmonics and minus all odd signal harmonics, thus reducing the number and power of frequencies which must be filtered out.

The usual ring modulator (10) consists of four varistors arranged in a lattice so that the direction of easy flow of current is continuous around the lattice. Each pair of lattice leads are connected to center tapped transformers. The signal frequency is usually introduced through one transformer, the output taken from the other transformer, and the carrier frequency via the center taps. However, the unit is completely symmetrical and the arrangement may be interchanged at will.

The carrier, being of much higher amplitude than the signal and of much higher frequency, acts as a switch which causes periodic phase reversing. This view is normally accurate enough. (26). Two units of the ring are, at any one instant, conducting, and two are non-conducting. Ideally the four varistors are identical in forward and backward resistance. Ideally the transformers are perfect. Under these conditions only odd carrier harmonics plus or minus odd signal harmonics will appear in the output. The even harmonics will remain in the ring.

As pointed out, the present manufacturing and grading techniques are such that random selection of four varistors whose characteristics are even moderately similar is highly improbable. It is necessary to make additional tests to grade and select matched varistors. Acceptable matching can be obtained by matching varistors whose forward currents at one or two voltage points are within a milliampere or so. Varistors which are so selected by this method will certainly be suitable for use in modulator units in which the signal frequency is a single frequency. This method is not entirely satisfactory for selection of units which must be used in modulators in which the signal frequency consists of several frequencies.

The essential features of these modulators are that distortion and crosstalk be at minimum value and that the units be capable of sustained operation with little or no maintenance. It is possible to select varistors so that the distortion and crosstalk effects are within the desired limits. The varistors inherently possess the requirement of sustained operation and little maintenance.

2. Rectifiers

Germanium varistors may be used as various types of rectifiers such as half wave, full wave, and bridge type. In this capacity, they have definite limitations as to voltage and current handling capabilities. Use of additional units in series or parallel or in series-parallel combinations permits increased voltage and current handling capabilities.

Unless the units so used are selected with care, the voltages and currents will not divide equally.

Since the frequency characteristics of the germanium varistor are much better than those of the copper oxide, being flatter to a higher frequency, the use of germanium in lieu of copper oxide in rectifiers of meters is of advantage. The meter is more stable since the aging characteristics of germanium varistors is better than those of copper oxide.

Germanium varistors could be used as probes for a-c meters replacing the small diodes now being used in some types of meters. The size of the probe could be considerably reduced.

Varistors are capable of being used in voltage doubling circuits. Used in this manner they could supply large values of voltage, but in general due to their inherent inability to handle large powers their use as rectifiers and doublers would seem to be somewhat limited.

3. On-Off Devices

There are many devices of this type in which varistors may be used. Some are as clippers, clampers, limiters, slicers, wave steepeners, and pulse generators.

By shunting a pulse generator by a varistor and bias voltage a limiter may be obtained. Using another varistor and bias voltage also in shunt but with the varistor poled opposite to the first, a slicer is had. The magnitude of the pulse used would be limited by the bias voltage and the inverse voltage rating of the varistor.

In a somewhat similar manner a varistor and bias voltage could be used as a d-c restorer. In this case the load resistance should be low enough so that the back resistance of the varistor is not able to effect it.

The low forward resistance of the varistor may be used to prevent overshoots in pulses. For example, a tuned L- C circuit which is pulsed by a steep wave can be made to produce a single positive half cycle if a varistor is placed in parallel with the tuned circuit. Also hanging a varistor from the grid of a multivibrator to ground will reduce the positive overshoot, steepen the wavefront and increase the frequency range.

They may also be used as relays and delay relays in telephone circuits.

4. Variable Resistance Devices

In all of the above uses the function of the varistor was dependent on the fact that the back resistance was different from the forward resistance. Use was not made of the fact that there is within a small voltage range from approximately zero to one volt a very wide change of resistance. Use of this feature in the telephone industry occurs in vario-losser units.

Vario-lossers, 'variable loss units', are those parts of compressors or expandors in which the change in loss or gain occurs. In the Western Electric 1A system the variolossers are classed as two terminal networks, the varistors being considered merely as an impedance inserted in the circuit. This two terminal type may be further divided into two classes, series and shunt. The shunt type is used in the backward acting vario-losser of the compressor. The series type is used in the forward acting vario-losser of the expandor.

In the backward acting type, the nonlinear circuit is shunted between the generator and amplifier. A portion of the output of the amplifier is rectified and fed to the non-linear element. This has the effect of varying the resistance of the non-linear element and since the ratio of output to input voltage is proportional to this non-linear resistance the output is changed. By proper choice of generator and amplifier impedances an exponential current voltage relation may be established (2).

In an analogous manner by rectifying a portion of the input and feeding it to a non-linear element placed in series between the input and the output amplifier an exponential current-voltage relationship which is the exact opposite of the first may be established.

Units of this type must be identical. There can be no way to insure that the same two units will always be used together. Therefore, the requirements for matching varistors is very strict. A very high degree of selection is required.

Relays using the principle of the variable resistance are feasible. The telephone industry is using many of the germanium varistors for various types of relays.

CHAPTER VI

FUTURE USES

There is another property which a high inverse voltage germanium crystal may have, that of being photosensitive. This property is a result of having a crystal which is partially N type and partially P type. The photosensitive effect will occur along the boundary between the two types. Crystals of this type may be obtained in two ways, one by manufacturing processes which omit the heat treatment, two by subjecting an N type crystal to bombardment by deutrons or neutrons taking care to shield the portion of the crystal that is to remain N type. (12, 18). This transformation of a portion of the N type crystal into P type is of a permanent nature.

Two types of photosensitive effects, the photodiode (4) and the photopeak, have been noted. The former is so called from the fact that for constant illumination the current saturates for a bias voltage of greater than one volt. The current is linearly dependent on the intensity of illumination up to a value of about 2 lumens per cm. The latter is so called from the characteristic of having a voltage maximum at a current of about one milliampere. There is a fairly extensive negative resistance region prior the current and voltage reach a linear relationship.

Thus by additional processes the present type varistor could be transformed into a photosensitive element which could be used for detectors, triggering devices operated by light, or oscillators.

A very recent development which was essentially an outgrowth of the original development of the germanium varistor is the transistor. This device has been called a crystal triode (7). In one form the transistor resembles a varistor which has two instead of one cat whiskers.

With a transistor amplifications of the order of ten to twenty may be obtained. Combinations of transistors and varistors have been used to supply all of the functions of vacuum tubes in a standard broadcast receiver. It is possible that these devices will ultimately completely replace the present day vacuum tubes in many applications.

The advantages of these units, varistors and transistors, are numerous: small size, no requirements for filament power, ruggedness, lack of maintenance problems, Serious drawbacks are: lack of uniformity from unit to unit, lack of power handling capabilities, noise figure of the transistor, limited operating range due to temperature, and sensitivity to temperature changes. Improvement of all or part of these must be made before widespread use of transistors in particular may be made.

In the case of the germanium varistor its major defects seem to be lack of uniformity from unit to unit and a somewhat limited operating temperature range. The lack of uniformity can be overcome by careful selection of units. Pushing the upper limit of the operating temperature range to over a 100° C. would increase the number of circuits in which varistors could be used.

The art of the semiconductor is a new one. Very great and rapid strides have been made in the past few years. The use of semiconductors of all types is increasing as new applications appear or improvements in the semiconductors are made. Continued improvements in types and wider use as more knowledge is gained is to be expected.

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